BOND STRENGTH MEASUREMENTS FROM AN AUSTRALIAN STANDARD BOND WRENCH IN COMPARISON TO THE UNBALANCED ASTM C 1072 BOND WRENCH TO THE BALANCED AND UNBALANCED WRENCHES

A Thesis

by

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ABSTRACT

Bond strength is one of the most important factors that affect the performance of the joint under various loading conditions. The flexural bond strength of a joint can be measured using a bond wrench. The first of the bond wrenches was developed in 1980s in the Australian laboratories. Former TAMU students had built a lightweight Indian unbalanced and balanced bond wrench. An Australian bond wrench was manufactured in 2011 and subsequently in 2012 an ASTM C 1072 Bond Wrench was developed.

Previous researchers have found out that no unacceptable bias existed in the flexural strength values forecasted using the Indian balanced and unbalanced wrench. The studies have also shown that there exists a bias between American Bond Wrench and Australian Bond wrenches. The Australian wrench values were significantly higher than the American bond wrenches for similar types of samples. Hence it was recommended that the tests be carried out by replacing the cement with Portland cement.

This experimental research uses Portland cement and a total of 50 prisms was built in two sets. Each prism comprised of six bricks with five joints, and all the bricks used were Texan bricks. The mortar used here was 1:1:6. The samples were cured for a period of 28 days, and all the experiments swere carried out under same weather conditions The first set prisms was tested using Australian and the American bond wrench., the second set of prims was tested using the other two wrenches.

A Student's t-Test analysis was run between the flexural strength values of the four wrenches. From the plots, it can be inferred that the mean value of the American wrench was low when compared with the mean values of the other three wrenches. The plots of Australian bond wrench and Indian unbalanced were quite similar.

It can be concluded that the values forecasted using the American bond wrench were statistically different from the other three wrenches, and the reason can be noted as the difficulty in using the American bond wrench.

Further research is recommended using the Texas red brick.

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CHAPTER I

INTRODUCTION

Background

Extensive research has been done with respect to the complex phenomenon involved in the formation of the bond between masonry units and mortar. (Edgell, 1987; Portland Cement Association, 1994). This paper provides a comparison of flexural strength results and checks bias among the four wrenches namely Australian, American, Indian balanced and unbalanced wrenches. This research builds on the works carried out by Chaudhari (2010), McHargue (2013) and Nichols (2013), comparing the results given by different bond wrenches. As a quality control instrument, for newly built masonry and for the in situ measurement of bond on existing structures, a laboratory bond wrench test was first developed in Australia.

The use of bond wrenches in the United States is based on the ASTM Standards C 1072 ASTM 2000 and C 1357 ASTM 2002 (Khalaf, F. M. 1993). Chaudhari (2010) and Jatin (2010) developed the Indian balanced and unbalanced wrench. The basic question is whether all these wrenches yield the same results for a sample of bricks under similar conditions.

Chapter II discusses t literature review, methodology is discussed in Chapter III, the results in Chapter IV and Chapter V contains the conclusions.

An important aspect of bond strength is ensuring that a minimum level of flexural strength is attained while construction, to resist the transient loads likes wind and earthquakes. The minimum acceptable value of non-seismic intense zones, such as

Houston, Sydney, Toronto or NY is often quoted as 0.1 MPa (R. E. Melchers, (Editor), 1990; R. E. Melchers & Page, 1992; Nichols, 1990, 1991).

This experiment uses extruded Texas bricks. The mortar composition used has one part lime, one part Portland cement, and six parts sand.

Problem statement

The research work is an attempt to determine if a statistical significant difference exists between the mean flexural strength results for the ASTM C1072 bond wrench, the AS3700 bond, the Indian balanced and unbalanced wrench for common brick and Portland prisms.

Hypothesis

The following hypothesis will be tested for the study:

There is no statistical difference that exists between the flexural bond strength results for ASTM C1072 bond wrench, AS 3700 bond wrench, Indian Balanced and Unbalanced wrench.

Limitations

The underlying challenge is the bias that exists between wrenches. The comparison of bond wrench results within a country and between countries have not been complete. The bond wrench has not reached any kind of acceptable standardization level because of its usage by a very limited number of groups.

Some of the key challenges that arise when developing and internationally accepted standards as listed by Nichols (2013) are:

1. Developing a testing method which includes moisture limits on the bricks and also exact mixture requirements for the mortar and testing schedules.
2. Avoiding the usage of a clamping mechanism which may pre-damage the joint that leads to a higher coefficient of variation of results.
3. Designing a simple clamping mechanism
4. Constructible in a small workshop with limited tools

Study limitations are:

1. The first population sample, Prism Set One, has 125 joints tested to failure, using American and Australian bond wrenches.
2. The second population sample, Prism Set Two, also has 125 joints to be tested for failure using Indian balanced and unbalanced bond wrenches.
3. The cement used is Portland Cement
4. Composition of mortar is 1:1:6 (lime: cement: aggregate) by volume has been used.

CHAPTER II

LITERATURE REVIEW

The literature study highlights the importance of flexural bond strength of masonry in design of walls, which are subjected to horizontal forces applied to the wall like the wind forces. The review discusses the masonry properties, bond characteristics and early research that has been performed to determine the flexural bond strength. There exists a variability of flexural strength when smallest samples constructed by the same mason, using same mortar mix, using same bricks from a single pallet are tested under the same weather conditions. Hence, this experiment intends to find out some of the reasons and causes for variability. The paper makes an effort to minimize the variations in variables associated with the experiment except for the kind of bond wrench used for testing.

A bond generally refers to two concepts between the mortar and masonry unit, one being the extent of contact and the other being the stress required to break the contact between them (Sise, Shrive & Jessop, 1988). The lower of the two values determines the flexural strength of each prism couplet. Masonry is weak under tensile stresses and strong under compressive stress (Lawrence S. J. 2008). The stress undergone may vary due to different factors. The tensile strength is dependent on type of masonry, mortar composition and the admixtures that have been added to the mortar. Nichols (2000) showed that pre-wetting a pressed brick not only affects the measured flexural strength, but also introduces a consistent bias in strength.

This strength is the property of the combination of mortar and masonry, how well they are bonded together rather than being property of mortar alone (Lawrence S. J. 2008).

The flexural strength is measured using a bond wrench. An engineer is concerned about supporting the loads as well as bond strengths to resist tensile stresses, whereas the owner looks for durability for the sake of low maintenance (PCA, 1994a, p. 1). However the additional workability is often at the expense of durability (Nichols, 2013b).

The Bond wrench test was developed in Australia. It was used in laboratory research on bond strength as a quality control instrument and for in situ measurement of bond on existing structures. Figure 1 shows the Australian bond wrench in action.

Bond wrench test

Bond wrench tests at TAMU have also been carried out in the past using the American bond wrench, the Indian balanced and unbalanced wrenches

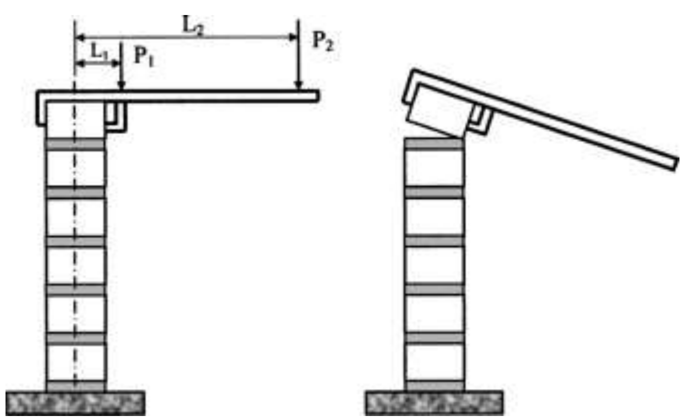


Figure 1: Bond wrench shown in position before the test and after bond failure

Initial works

Many researchers and research groups have done different research and set up procedures to investigate flexural bond strengths. Initial works were carried out by Baker (1914) tested the tensile strengths of cement mortar. Some of the tests include the bond wrench test, the bench test, bridge pier test, crossed couplet test, test on wallets (small walls) and the direct tensile test. All these tests have their own drawbacks and problems (Khalaf, F. M., 1963).

Crossed brick couplet test method

Failure was induced without pulling the specimen and this test uses crossed couplet specimens to establish the bond strength. This test measures a direct tensile strength of the bond between the mortar and the masonry unit. The crossed brick couplet tensile test evaluates mortar-brick bond strength and conducts a direct test on a pair of cross bricks separated by a mortar joint. To convert the conventional compression-testing machine’s downward force into a direct tension force shown in Figure 2, a test jig is used. Higher stresses get concentrated in the corners of the composite interface as the tensile stresses over the joints are not uniform. There exists variability and a wide scatter in results at areas subjected to high stress due to shrinkage stresses or due to their preparation during construction (Portland Cement Association, 1994a). Figure 3 gives the plan and section view of the set up.

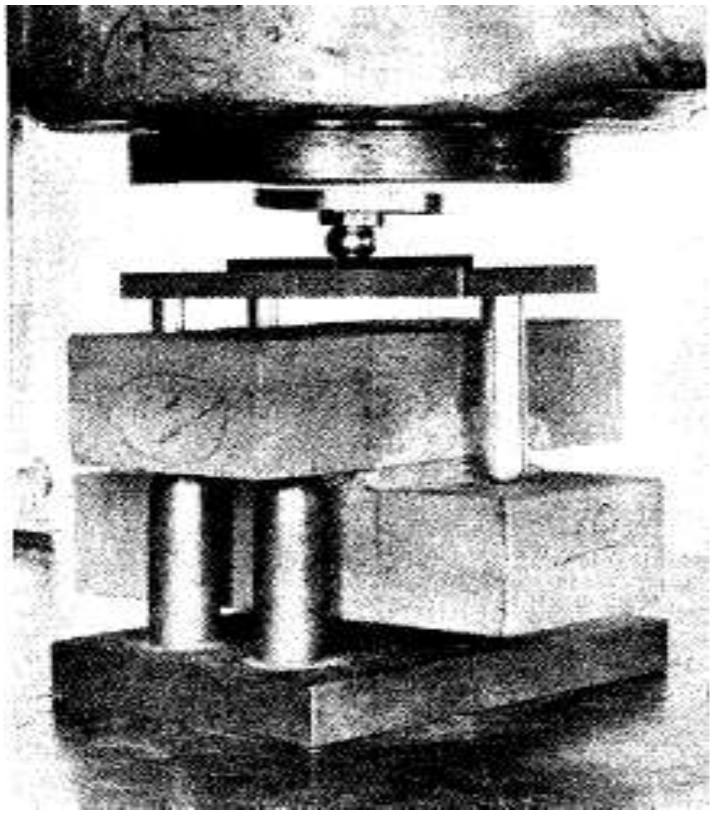


Figure 2: Crossed brick couplet test method

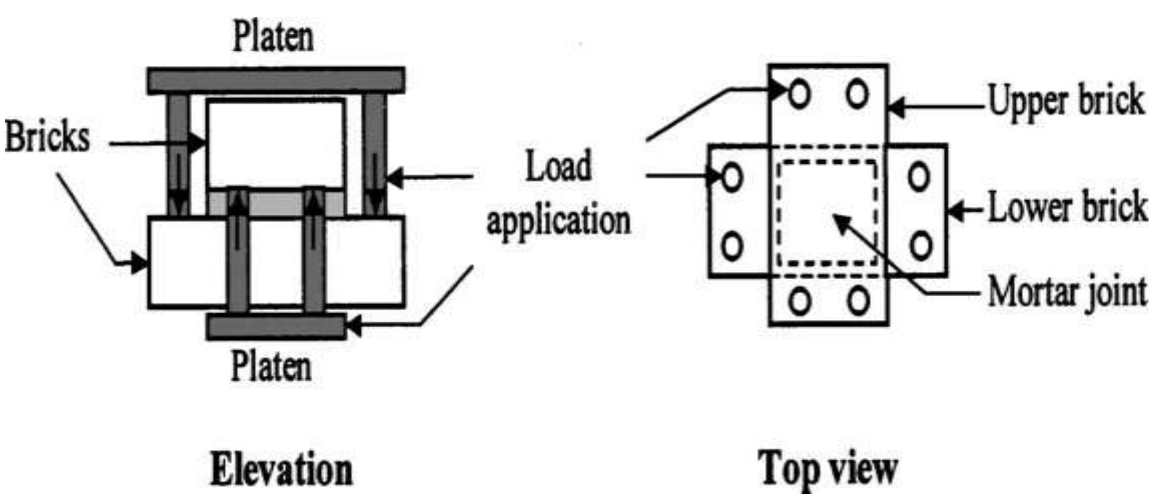


Figure 3: Elevation and top view of the corresponding setup

Couplet brick test through holes

This test uses the regular couplet as bolt-holes which run between a steel plate and through the middle of masonry units to apply opposing forces of tension. This test was used by Riddington and Jukes (1994) to determine and compare the results of bond strengths. This test was favored for the following reasons: (a) it's quick and can be administered easily (b) It was found that results were consistent.

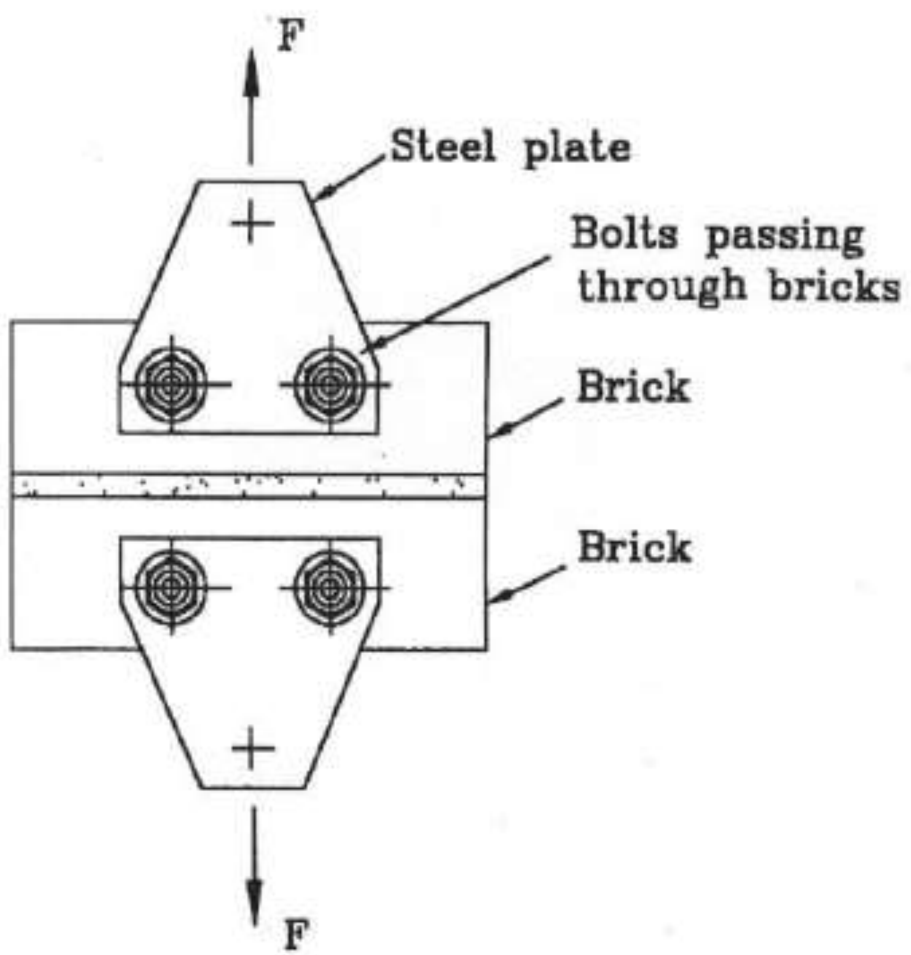


Figure 4: Bolt through holes test, Riddington, Jukes and Morrel (1998)

A lot of different brick and mortar combinations were used. This test concludes that a direct tensile test is most likely to give a representative value for bond strength than the bond wrench test (Jukes et al. 1997). Figure 4 gives a better idea about the test.

Test on walletes

Very popular and a well-known standard for the test is the BS 5628 (British Standards Institution, 1992).

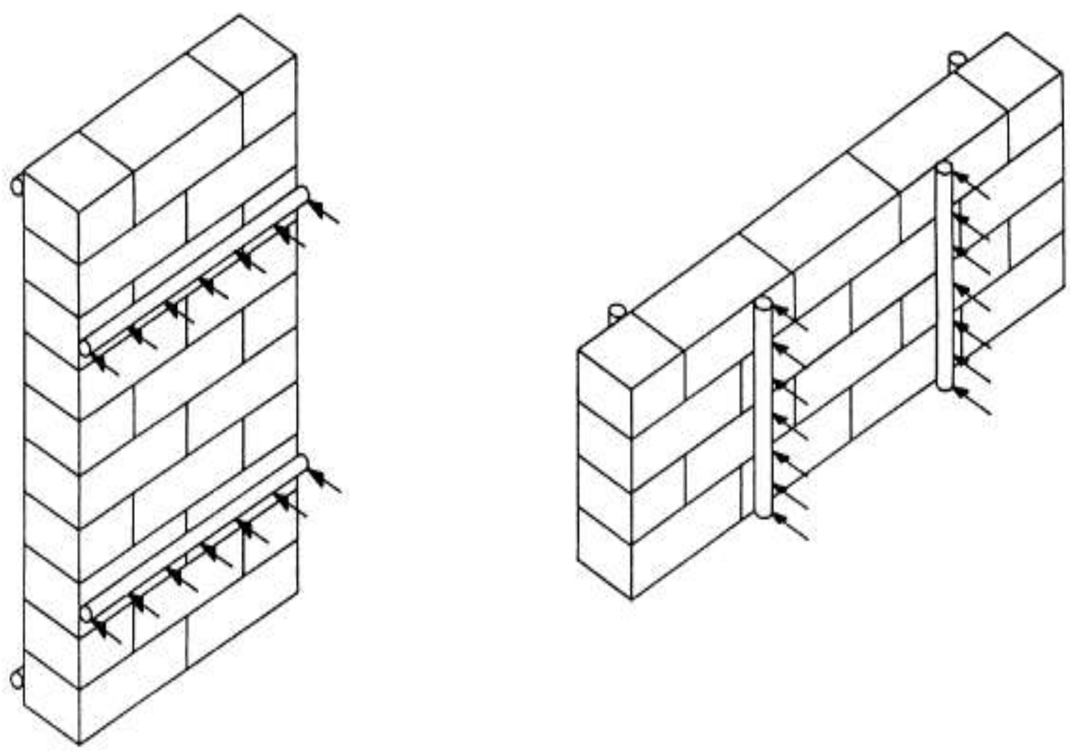


Figure 5: Brick walletes testing to BS 5628-1:1992

The researchers had compared results from the several cross coupled tests with those of test on wallettes tested in accordance with BS6528. It was found (Figure 5) that test from wallettes was higher than the couplet test.

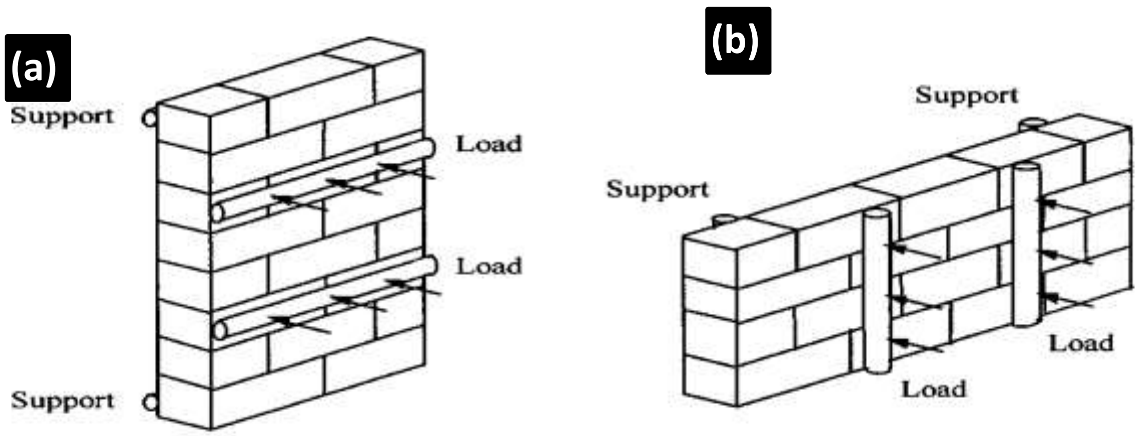


Figure 6: (a)Plane of failure parallel to bed joint
(b) Plane of failure normal to bed joint

There is a difficulty with this test as a large specimen and a set-up is required which can make the whole process cumbersome to perform. A four point loading system is used for deriving the flexural bond strength of the joints as shown in the Figure 6.

Figure 7 conforms that the values from wallettes test is higher than the crossed couplet bond strength values on the same sample.

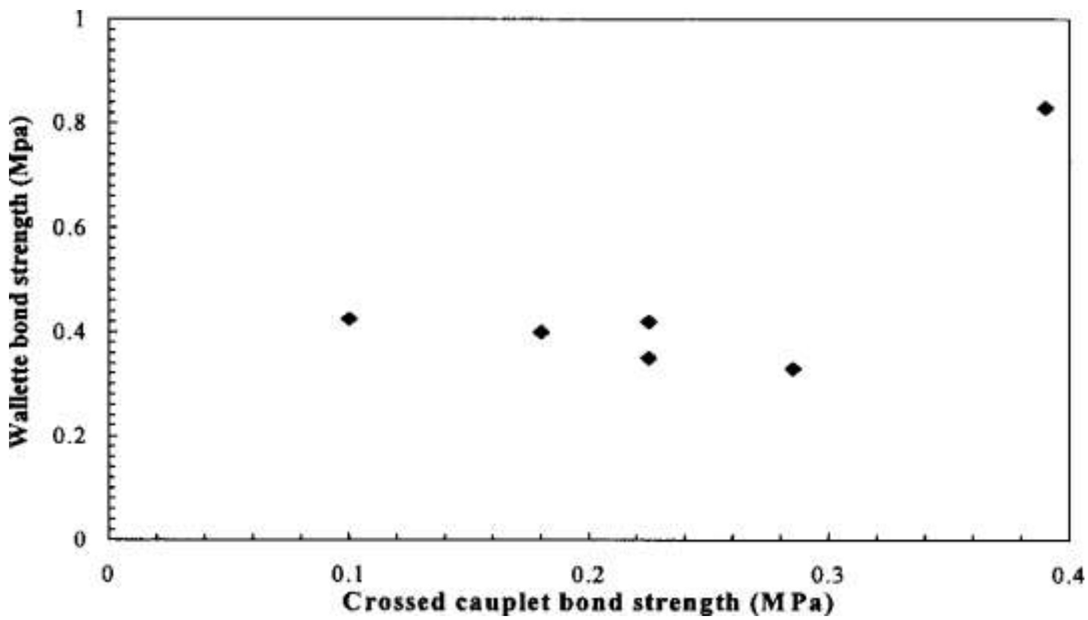


Figure 7: Comparison of bond strengths from crossed couplet bond strength and test on wallettes

Bridge pier test

Bridge test was adopted as the ASTM standardized test method ASTM E 518 (ASTM International, 2010). These test methods are intended to provide simplified means for gathering research data on the flexural bond strength developed with different types of masonry untis and mortar or for purpose of checking the quality of the job (materials and workmanship).

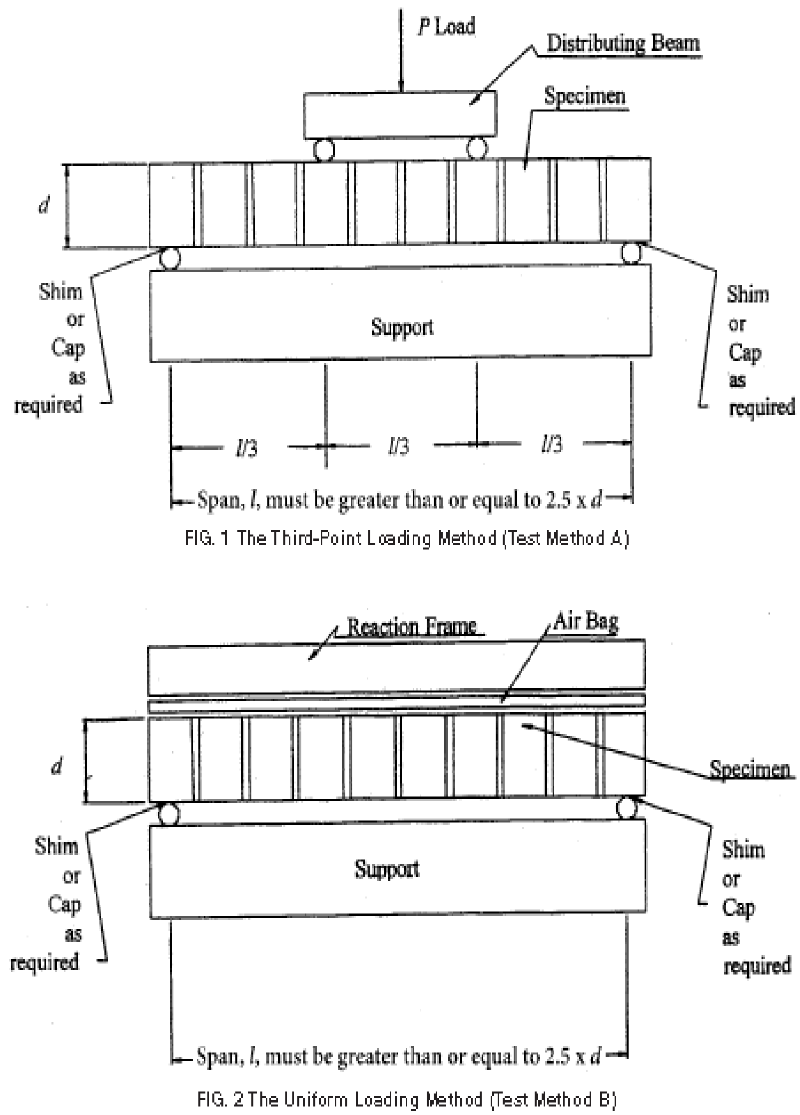


Figure 8: ASTM E528 Test methods A & B

ANSYS was used by Riddington et al (1998) to complete a finite element analysis to model the bridge pier test. This experiment was found to be uneconomic in terms of quantity of materials used and effort that is being put to produce the masonry specimen.

Bond wrench types

The first bond wrench was created by Hughes and Zsembery (1980), as shown in Figure 8. The test is a variant of the bond beam test.

Figure 9 shows the distinct step, second stage of the set-up of the bond wrench.

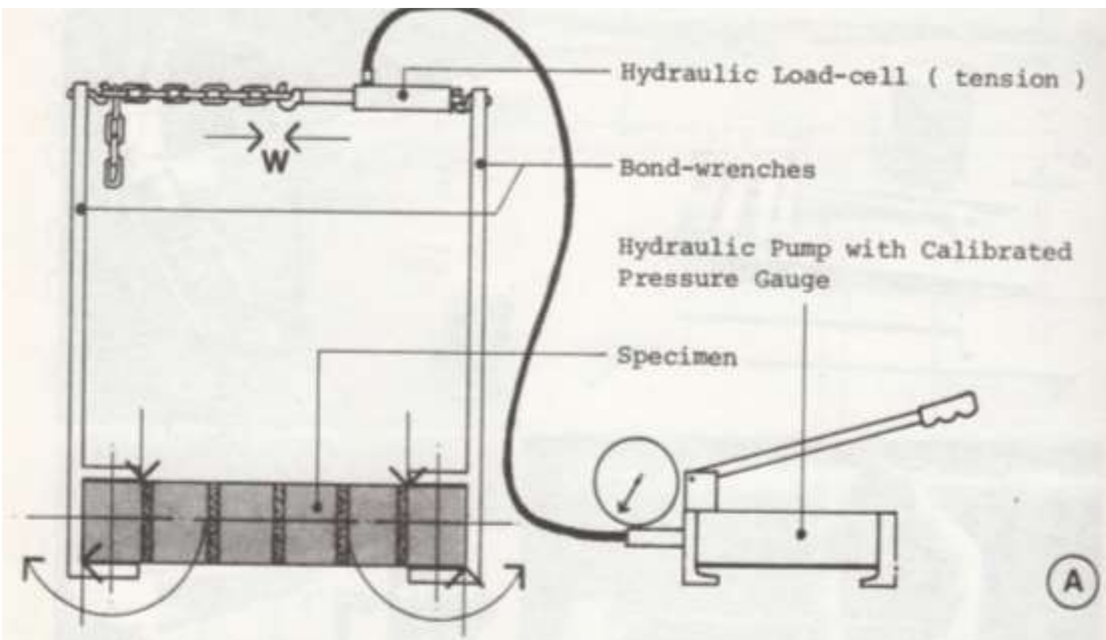


Figure 9: Bond wrench stage I

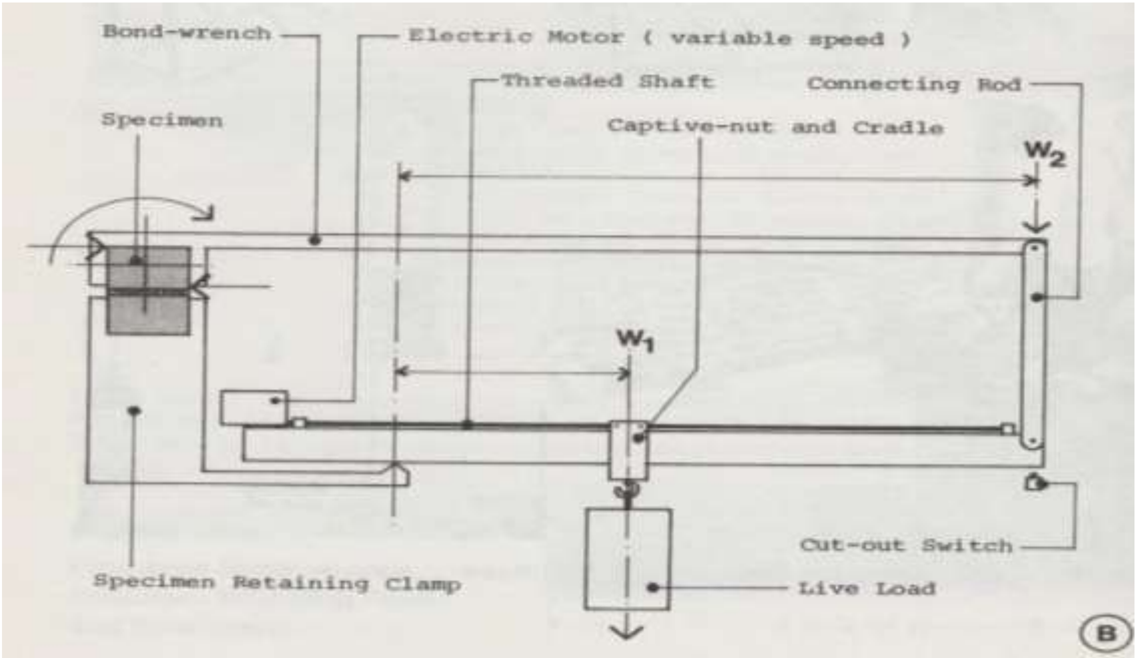


Figure 10: Bond wrench stage II

There have been a lot of different bond wrenches that have been developed in the past without modifying the basic structural form of the original structure shown in Figure 10. The bond wrench has two parts, the lower part having a base mechanism to clamp the prism to the base, and the upper part is the wrench that applies the moment to the uppermost brick.

Extensive investigations were carried out by Rao (1996) on the flexural bond strength of a masonry using a bond wrench test setup and the major conclusions of these were.

- Flexural bond strength increases with an increase in mortar strength for cement mortar irrespective of the type of masonry unit.

- Composite mortars like soil-cement mortar and cement- lime mortar had shown better bond strength than the cement mortars. Also, the brick strength did not have any significant effect on flexural bond strength.
- The moisture content of the brick at the time of casting and laying had a significant effect on flexural bond strength. An optimum moisture content leads to maximum bond strength.

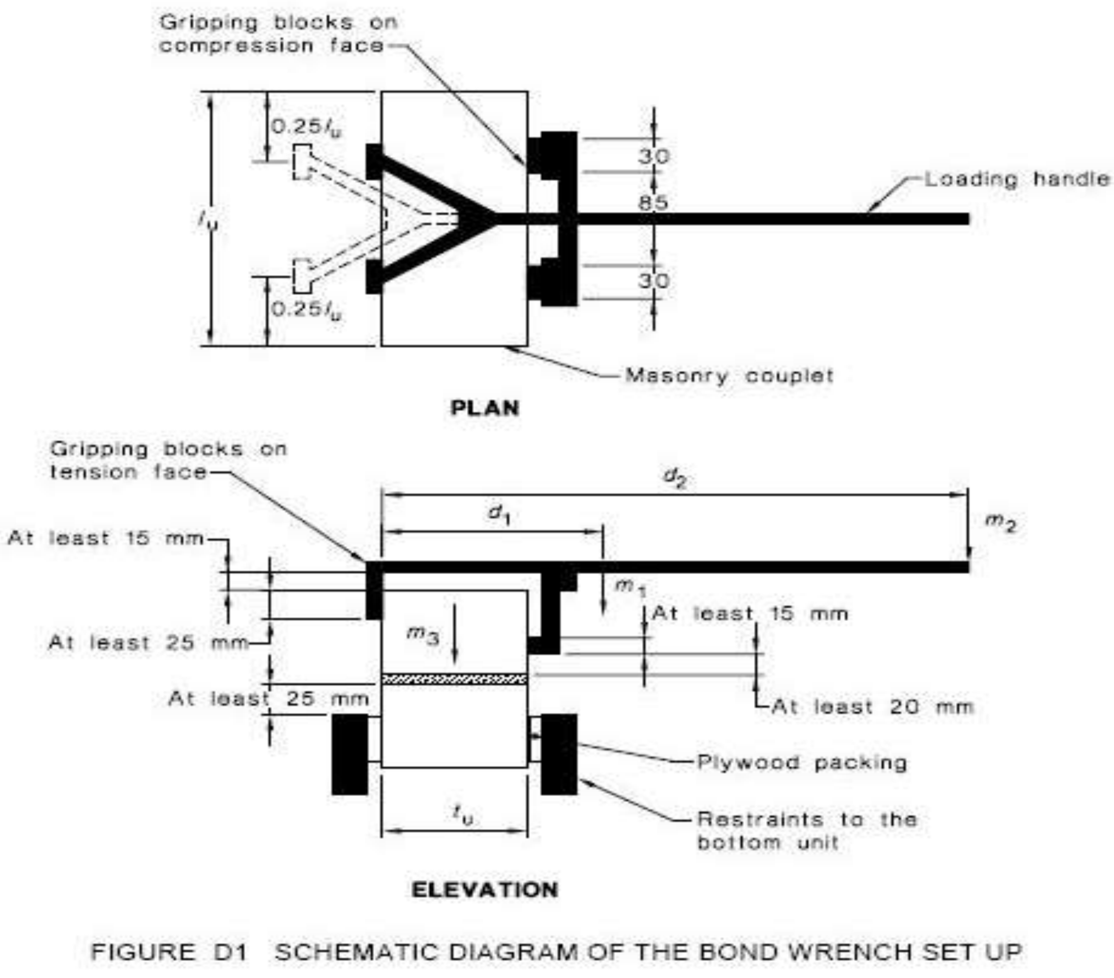


Figure 11: Bond wrench set up

Four different wrenches have been made at TAMU. These are namely:

(a) American Bond Wrench ASTM C 1072 Bond Wrench has,

   (i) Has the shortest arm among all the bond wrenches

   (ii) Highest mass

   (iii) Numerous moving parts

(b) Australian Bond Wrench (2001), which has

   (i) A long moment arm

   (ii) Intermediate mass

   (iii) Two moving parts

(c) Indian balanced bond wrench

   (i) A long moment arm

   (ii) Light mass

   (iii) No moving parts and simple plans

(d) Indian Unbalanced bond wrench

   (i) A long moment arm

   (ii) Light mass

   (iii) No moving parts and simple plans

Prior research by Chaudhari (2010) and McHargue (2013) have all focused on developing of bond wrenches and check if there exists any bias between different test methods. The research using masonry cements did show that there exists a bias.

Bond wrench designs

Additional flexural data obtained using a bond wrench test gives values for a masonry test specimen that is tested. The above test overcomes the inefficiency of the pier test and also provides more statistical data for masonry test pier (W. Samarasinghe, Lawrence, & Page., 1999)

It was found by McGingley (1996) that the linear stress distribution assumed by flexural theory does not hold good for ASTM Standard bond wrench, and the existing stress distributions are a result of measurements determined using LVDT system. The percentage of axial stresses, have increased relative to the peak flexural stress.

Riddington, Jukes and Morrell (1998), in their analysis of masonry bond tests had identified that a bond wrench test must be capable of producing a simple bending-theory stress distribution, although care needs to be taken so that the stress distribution does not get affected by the clamping mechanisms or wrench not being the full length of the specimen being tested.

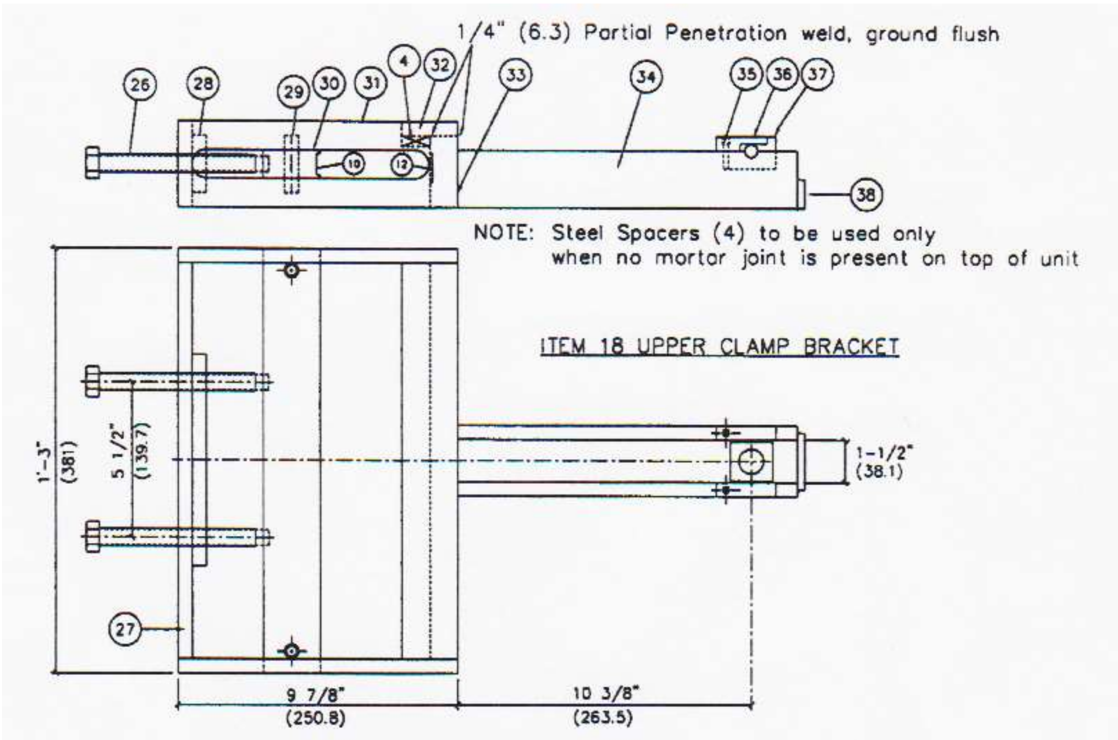


Figure 12: ASTM C1072 Bond wrench clamp bracket

Radcliffe and Bennett (2004) had noted that an unbalanced stress distribution happens across a masonry prism cross section when bond wrenches are used. This particular stress distribution has a couple of components, uniform axial compressive stress distribution and a linear flexural stress distribution. The flexural stress distribution is inversely proportional to length of loading arm due to the impact of the compressive load. Hence, having a longer loading arm has a lower compressive stress load, resulting in a lower impact or influence on the total stress distribution, due to compression and flexural stresses.

Figure 13 depicts the Australian Bond Wrench, AS 3700 used in the present experiment, which has a longer moment arm and lower mass than the American Bond Wrench.

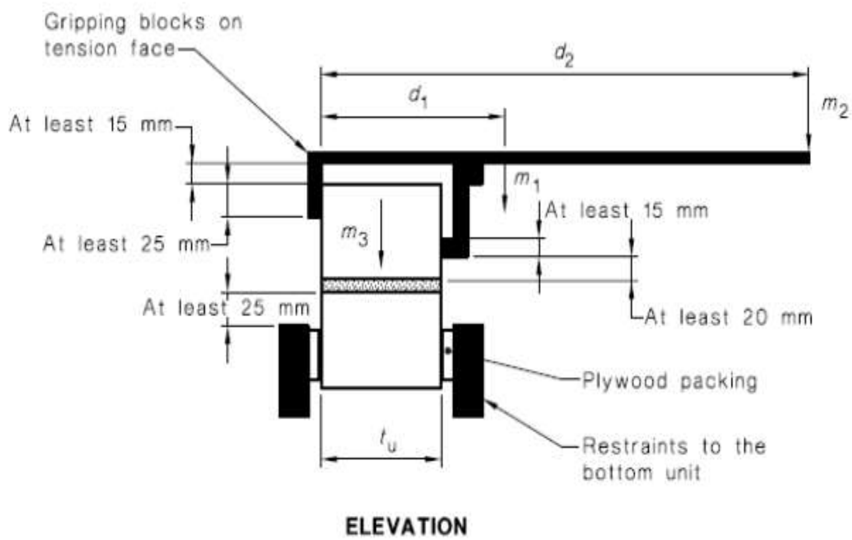


Figure 13: Australian bond wrench diagram AS 3700

Modified bond wrench

Figure 14 refers to the pure couple bond wrench created by Radcliffe, Bennet and Bryja (2004) using the ASTM C 1072. The intent of the design is that the upward load negates with the downward testing load, hence the weight of the clamping mechanism is the only compressive load left. The research intends to ensure the sum of forces in the vertical directions in the pure couple bond wrench is zero.

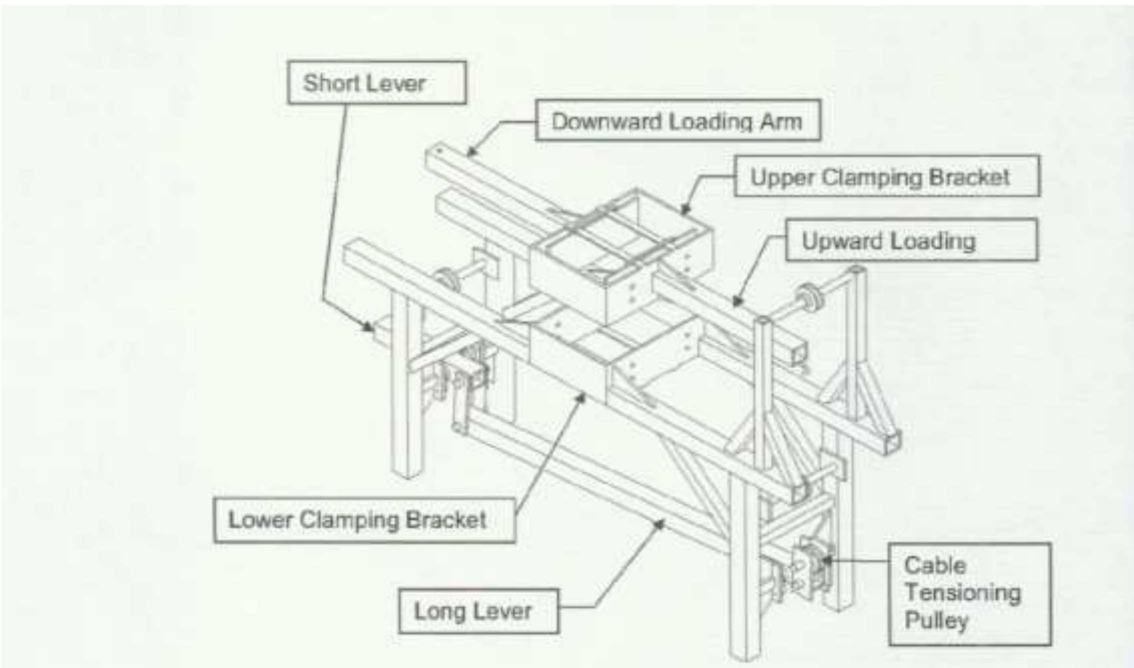


Figure 14: Pure couple bond wrench

Nichols (2013) had identified a negative attribute to the American bond wrench to a larger extent and a lesser extent to the Australian bond wrench. These wrenches created a moment before the external load was applied. The induced moment depended on the mass of the bond wrench and the center of gravity of the wrench. During their research on soft mortars, an Italian group had found out the concept of a balanced bond wrench which was in lines with the conceptual idea put forth by Radcliffe, Bennet and Bryja (2004). It is also simpler to construct. (Baronio et al., 2003; L. Binda, 2008; L. Binda et al., 2003; L. Binda et al., 2000; Luigia Binda, Saisi, & Zanzi, 2003; Facchini, Zanetta, Binda, Roberti, & Tiraboschi, 1995).

Figure 15 gives an idea about the Indian balanced wrench developed by Chaudhari, designed to impart zero moment at the start of the test to the top of prism used in testing.

Figure 15: Indian balanced bond wrench (Chaudhari, 2010)

A counter balance extension in the opposite direction of the apparatus's loading arm was added by Chaudhari (2010) and a balanced bond wrench was developed. Hence the unbalanced stress generated, due to the self-weight of the wrench and its center of gravity, is negated. The Indian unbalanced wrench developed at Texas A & M is illustrated in Figure 16.

Figure 16: Indian unbalanced bond wrench test

Table 1

Balanced to unbalanced test results

Flexural Strength (MPa)	Unbalanced Bond Wrench		Balanced Bond Wrench	
	Researcher I	Researcher II	Researcher I	Researcher II
	0.762	0.813	0.472	0.661
	0.773	0.533	0.579	0.701
	0.645	0.813	0.740	0.472
	0.533	0.690	0.691	0.759
	0.706	0.730	0.759	0.691
	0.645	0.794	0.722	0.661
	0.813	0.794	0.661	0.722
	0.832	0.533	0.638	0.759
	0.773	0.832	0.661	0.606
	0.705	0.730	0.691	0.472
Mean (μ)	0.72	0.73	0.66	0.65
Standard	0.09	0.11	0.08	0.10
COV	0.13	0.15	0.13	0.16

Chaudhari (2010) developed the balanced wrench and Yadav had developed an unbalanced wrench. They had worked to determine the difference that existed in the flexural results between the two wrenches. The idea about the unbalanced wrench was from the work carried out in Italy on soft mortars (L. Binda et al., 2000). The difference between balanced and unbalanced bond wrench is that the latter does not have a balancing arm. ACME brick was used in the research carried out by Chaudhari (2010). The mortar mix used was 1:1:6. Table 1 gives the flexural stress results for two masons.

The analysis of the results obtained from unbalanced test and the balanced wrench using a Student's t Test, with a 5% acceptance level shows that they yield statistically different results, the flexural strength values ranged from 0.65 MPa – 0.73 MPa.

Nichols (2013) had tested Chaudhari's (2010) bond wrench with Australian bond wrench model, ASTM C 1072, an equivalent unbalanced wrench. The summary of the results of the four wrenches has been depicted below in Table 2. A total of eleven prisms was tested. The results showed that the American wrench results were on average fifty percent higher than the other three tests. The mean was distinct and different from the other three sets. Also, the student's t test results with a five percent acceptance level shows that the results from unbalanced, balanced and Australian bond wrenches were statistically indistinguishable (Miller & Freund, 1976).

Table 2

Test results – Failure load and Peak stress (MPa)

Prism/Brick	Test Wrench	Failure L (kg)	Stress (MPa)
1-1	Australian	9.97	0.55
1-2	American	34.53	1.14
2-1	Unbalanced	25.36	0.81
2-2	Failed in setup	0	0
2-3	Failed in setup	0	0
2-4	Balanced	17.45	0.58
3-1	Australian	10.72	0.59
4-1	American	26.42	0.96
4-2	Unbalanced	51.28	1.63
4-3	Balanced	30.73	1.02
5-1	American	52.25	1.53
5-2	Australian	17.09	0.90
5-3	Balanced	17.07	0.57
5-4	Unbalanced	21.00	0.63
6-1	American	57.87	1.65
6-2	Australian	28.65	1.46
6-3	Unbalanced (smooth bond failure)	10.80	0.38
7-1	Balanced	12.58	0.42
7-2	American	75.35	2.03
7-3	Australian	23.12	1.19
8-1	Unbalanced	9.43	0.30
8-2	Balanced	40.71	1.35
8-3	Failed in American Setup	0	0
9-1	American	28.28	1.00
9-2	Australian	21.42	1.11
10-1	Unbalanced	29.25	0.94
10-2	Balanced	31.65	1.05
11-1	American	16.09	0.74
11-2	Australian	6.64	0.39
11-3	Unbalanced	39.14	1.21
11-4	American	41.73	1.30

Types of flexural failures

Sarangapani et al, (2005) had utilized different flexural tests, various mortars and a modified ASTM C1027 bond wrench in their research that pertained to masonry bond and compressive strengths. It has been noted that the flexural prism failures fall into one of the three categories that have been mentioned below.

Type 1: Failure at the brick-mortar interface indicating the bond failure, refer to Figure 17.

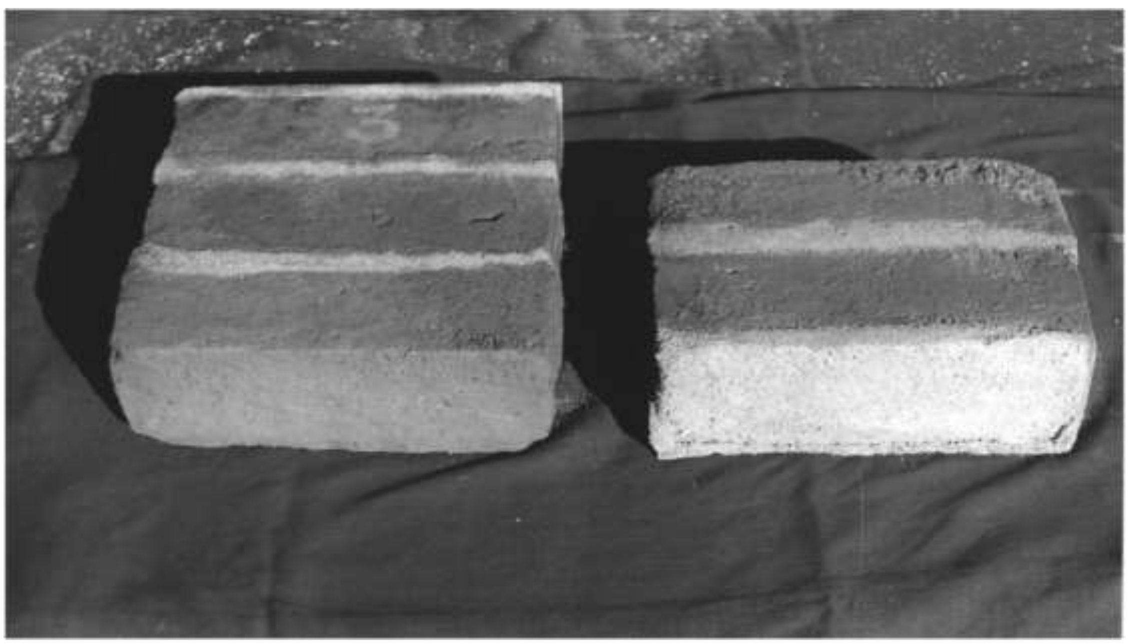


Figure 17: Bond failure at brick-mortar interface

Type 2: Failure of brick in flexure with brick-mortar interface intact, refer to Figure 18.

Figure 18: Bond failure when the mortar is still intact

Type 3, which is a combination of Type 1 and Type 2 Failure as shown in Figure 19.

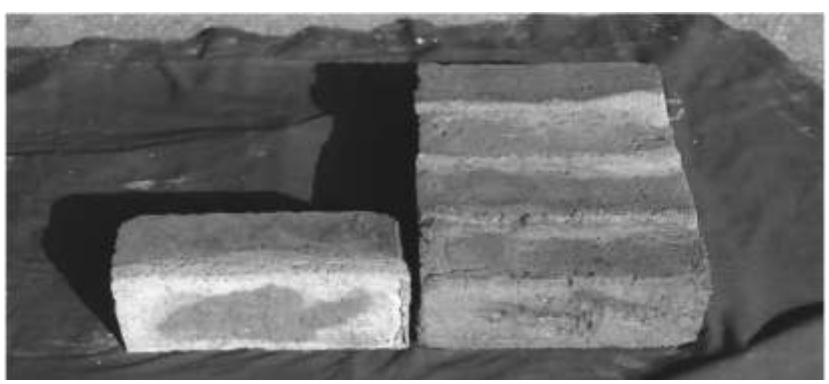


Figure 19: Type 1 and Type 2 failure

Water retention, initial flow, air content and workmanship are some of the well-known properties of mortar that can influence the bond strength (Boynton & Gutschick, 1964; Edgell, 1987) . Earlier works by Kampf (1963) indicated that workability is not a single property, but a combination of many factors and is the most important property that affects a good bond.

Fishburn (1961) had conducted studies using different mortars which differed in the cementitious materials and had noted that there appeared to be some kind of relationship that exists between the flexural strength values of tested walls and the compressive strength of the mortar. Chaudhari (2010) and Eric (2013) had used masonry cement in their research, but this research paper uses Portland cement and Figure 20 shows that higher bond strengths may result using mortar with a higher percentage of Portland cement.

Some of the conclusions of Palmer and Parsons (1934) are:

- If the extent of bond formation was good, it was noted that the maximum bond-strength results from fifteen different mortars increased with the compressive strength of mortars.
- Bricks which were porous and had a low rate of absorption acquired highest bond strength with mortars of high strength, if the extent of bond was good.

Timeliness of brick setting has a significant effect on the bond strength, as the bond strength reduces when there is a delayed setting of brick onto the mortar bed (Boynton & Gutschick, 1964; Ritchie & Davison, 1962). Kampf (1963) had mentioned that this bond strength reduction is the maximum for high suction brick and lowest for low suction bricks. After the brick mortar begins to stiffen, if the bricks are realigned then the bond gets destroyed (Boynton & Gutschick, 1964), the window of opportunity for realigning of brick without getting destroyed is greatest for low –suction brick and high water- retention mortar, refer to Figure 20 and Figure 21.

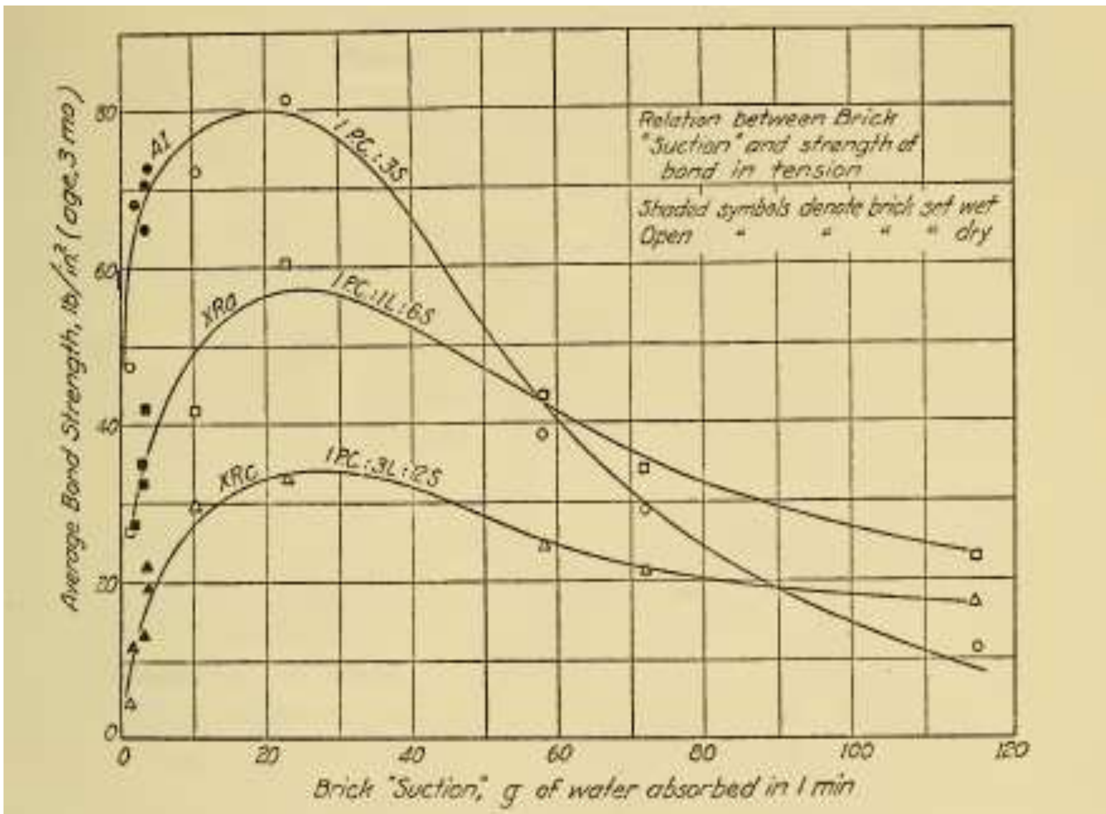


Figure 20: Bond strength results across a range of brick suction values

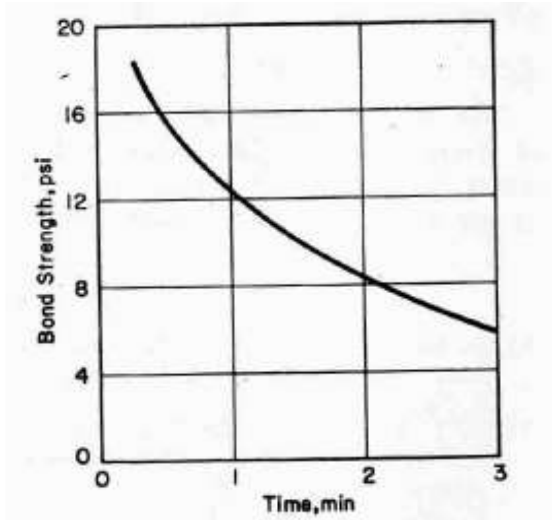


Figure 21: Bond strength plotted against time to placement Kampf (1963)

Bond wrench results have been published for different wrench designs on a continuous basis. The initial test series at TAMU, by Chaudhari (2010) and Jatin Yadav Singla (2010), have showed that the unbalanced wrench yielded ten percent higher results than the balanced wrench. The next test results at TAMU have shown that the four bond wrenches yield different results when tested under similar conditions (Nichols, 2013). The American bond wrench ASTM C 1072, gave results so far that are fifty percent higher than the Australian bond wrench. In his test series, no statistical difference was observed between the other three wrenches, although it was a limited test set. McHargue (2012) in his test using masonry cements had noted that the Australian bond wrench had results that were thirteen to sixteen percent higher than the American bond wrench. Also, his results showed a slight, but statistically significant, increase in the test strength as the testing proceeded for both bricks which could have been due to improvements in manufacture of prisms or the way the tests have been carried out.

CHAPTER III

METHODOLOGY

Introduction

This research work includes manufacturing of prisms using Portland cement mix and the testing is done with four types of bond wrenches. Methodology covers the experimental procedure, the material used, brief descriptions about the equipment, experimental measurement issues, different bond wrench procedures and the data analysis methods.

Experimental procedure

The basic elements of this research is to investigate if any bias exists between the values got from the four bond wrenches, i.e ASTMC 1072 American Bond Wrench, AS 3700 Australian bond wrench, the Indian balanced and the unbalanced bond wrench. The standard procedures outlined in the ASTM C1072 (ASTM International, 2013c) will be followed for this experiment.

Figure 22 shows the mixer used in the experiments. Figure 23 shows the typical brick used for this experimental work.

Figure 22: Concrete mixer and bricks

Figure 23: Typical brick used in the experiment

Figure *24* shows a typical bricks used for this experiment. Brick prisms were built by laying 6 bricks vertically with mortar. Only one proportion of mortar was used 1:1:6 (cement: lime: sand). The mortar was made in concrete mixer using Portland cement.

Figure *24* shows the samples that have been cured for 28 days and Figure 25 the materials.

Figure 24: Bricks laid for the experiment

Figure 25: Sand and lime

A total of fifty prisms (250 joints) have been casted as two separate sets of twenty five prisms each. The first set of prisms would be tested with the Australian and the American bond wrench, the second set using the Indian balanced and unbalanced.

Figure *27* shows the hydraulic jack that has been used for the experiment, Figure 26 shows the loading table being fixed inside the main frame to carry on the experiment.

Figure 26: Main frame bond wrench

Madhusudan will be assisting in the present paper, as his paper concentrates on comparing the results between the American and Australian bond wrench. The main frame was manufactured by Chaudhari (2010) and it had the following dimensions, Height: 36 inches, Width: 22 inches, Breadth: 34 inches. Figure 28 shows the method.

Figure 27: Hydraulic jack

Figure 28: Setting up the frame and hydraulic table for placing bricks to be tested

The prism is placed over the loading table, a bucket is used to apply the sand load to the end of the bond wrench moment arm. Figure 29 shows the sand method underway.

Figure 29: A bucket used to apply sand load to end of bond wrench moment arm

Experimental set up

The test set up:

- Uses the same base equipment for all the experimental works. The equipment used are the hydraulic jacks, main frame, ropes to hold the American bond wrench, hooks for holding the buckets etc.
- Uses a hydraulic table, as shown in Figure 25, which has been positioned in the center of main frame, to place bricks for testing.
- A lever is present to lift the table vertically upward to sit in the location within the lower hydraulic clamping bracket.
- Uses the hydraulic jack to apply pressure to lower clamping bracket to hold the masonry specimen tightly in place when testing is being done.
- Figure *30* and Figure 31 shows them.
- Clamp the bond wrench to the top of masonry unit of the specimen in the manner in which the arm is horizontal for the test.
- Place the bucket on one side of loading arm as shown in
- Figure *29* to the upper clamping bracket.
- Add sand as the counter weight, until the failure occurs in the joint, as shown in figure

Figure 30: Placing the hydraulic jack against the lower clamping bracket

Figure 31: Fixing up the hydraulic jack against the sample to apply pressure

Analysis

Figure 32 shows the schematic setup and the variables used in the analysis.

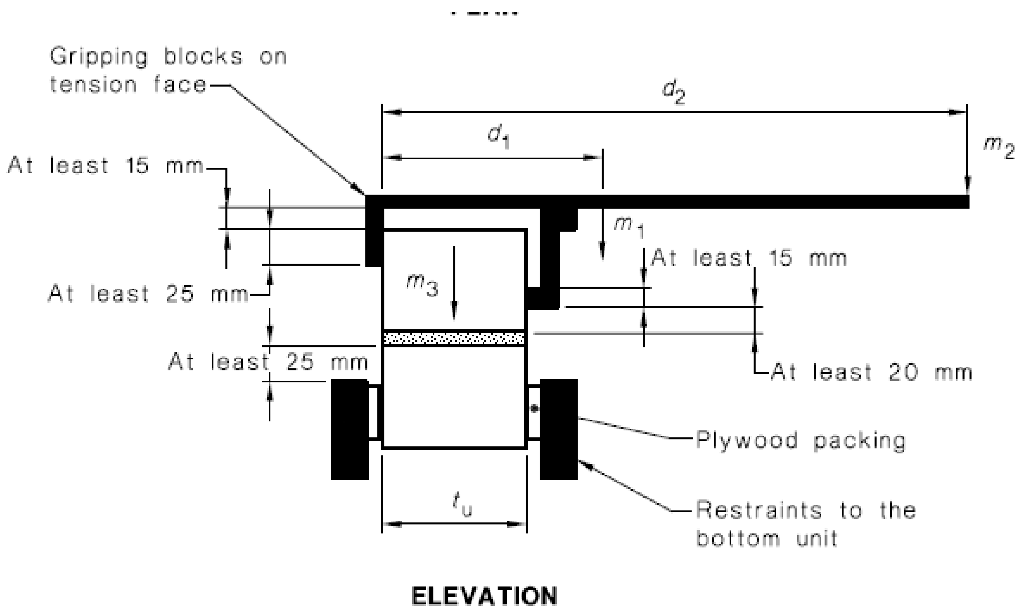


Figure 32: Schematic diagram of bond wrench set up

The flexural strength of each test joint of the specimen shall be determined using eq(1)

$$f_{sp} = (M_{sp} / Z_d) – (F_{sp} / A_d) \quad (1)$$

where,

f_{sp} = the flexural strength of the specimen, in mega Pascals

M_{sp} = the bending moment about the centroid of the bedded area of the test joint at failure, in Mewton millimeters

$= 9.81m_2 (d_2 - t_u / 2) + 9.81m1 (d_1 - t_u / 2)$

Z_d = the section modulus of the design cross-sectional area, (Ad) of a member

F_{sp} = the total compressive force on the bedded area of the tested joint, in N

$= 9.81 (m_1 + m_2 + m_3)$

A_d = the design cross-sectional area of a member

m_1, m_2, m_3 = the masses of components used in flexural strength testing, in kilograms

d_1 = the distance from the inside edge of the tension gripping block to the centre of gravity, in millimeters

d_2 = the distance from the inside edge of the tension gripping block to the loading handle, in millimeters

t_u = the width of the masonry unit.

CHAPTER IV

RESULTS

Introduction

This chapter gives a summary of the results of the experimental works carried out for this research. The chapter outlines the flexural strengths and the results. Table 3 shows the brick measurements.

Table 3

Brick measurements

Length	Width	Area
196.85	95.25	18749.96
195.26	89.69	17513.83
194.47	92.87	18060.07
194.47	91.28	17751.35
196.85	92.08	18124.96
193.68	92.08	17832.63
192.88	92.08	17759.54
195.26	85.73	16738.88
196.06	88.11	17273.78
196.85	88.90	17499.97

Note: All dimensions in mm

The average length of the brick is noted as 195.26 mm, width is 90.81 mm and an area of 17730.50mm^2.

Flexural strengths

To calculate the flexural strengths we need to have the self-weight of the wrench (m_1), self -weight of the brick (m_3) and the failure load (m_2), the distance from inside edge of tension gripping block to the center of gravity (d_1) in mm, the distance from the edge of the tension gripping block to the loading handle, in mm (d_2), the width of the masonry unit (t_u). The mass (m_3) of the brick is 1.57 kg's. Table 4 shows the measurements of the bond wrenches for the analysis.

Table *4*

Measurements of each of the bond wrenches

Variable	Australian	American	Balanced	Un Balanced
d_1	317.5	142	115.8	196
d_2	965.2	393.7	711.2	698.5
m_1	4.64	15.2	5.75	4.19

Note: Lengths in mm and Weight in kgs

The design analysis is:

Design Cross-sectional area of a member (A_d) in mm^2 = 17730.5 mm^2

Section modulus of the fractured section of the beam = 188963.3 mm^3

$$(Z_d) = (bh^2/6), \text{ in cubic millimeters}$$

Total compressive force on the bedded area of the tested joint (Fsp), in Newton = 9.81 ($m_1 + m_2 + m_3$)

Bending moment about the centroid of the bedded area of the test joint at failure (M_{sp}), in newton millimeters = $9.81m_2(d_2 - t_u/2) + 9.81m_1(d_1 - t_u/2)$

Flexural Strength of the bond wrench (f_{sp}), in MPa = $(M_{sp} / Z_d) - (F_{sp} / A_d)$

Table 5 shows the results for the first twenty samples. Table 6 shows the results for eighteen samples for the Australian bond wrench. Table 7 shows the first twenty samples for the American bond wrench and Table 8 shows the remaining US test results. Table 9 shows the results for the Indian balanced wrench for samples 1 to 22. Table 10 shows the remaining results for the Indian balanced wrench. Table 11 shows the results for the Indian unbalanced wrench for sample 1 to 22 and Table 12 shows the remaining results up to forty and Table 13 shows the results from 41 to 49.

Table 5

Flexural strength of the samples 1-20 using Australian bond wrench

No	m_2	F_{sp}	M_{sp}	f_{sp}
1	15.85	216.41	155403.4	0.8102
2	14.26	200.81	141056.5	0.7351
3	19.84	255.55	191406.0	0.9985
4	12.96	188.06	129326.3	0.6738
5	3.58	96.04	44688.5	0.2311
6	21.36	270.46	205121.3	1.0703
7	23.54	291.85	224791.9	1.1731
8	19.43	251.53	187706.5	0.9792
9	18.45	241.91	178863.7	0.9329
10	23.40	290.47	223528.6	1.1665
11	21.60	272.82	207286.9	1.0816
12	20.87	265.65	200699.9	1.0471
13	21.50	271.84	206384.5	1.0769
14	19.12	248.49	184909.3	0.9645
15	11.16	170.40	113084.5	0.5888
16	10.05	159.51	103068.7	0.5364
17	23.54	291.85	224791.9	1.1731
18	3.10	91.33	40357.4	0.2084
19	21.96	276.35	210535.2	1.0986
20	23.00	286.55	219919.4	1.1477

Table 6

Flexural strength of the samples 21-38 using Australian bond wrench

No	m_2	F_{sp}	M_{sp}	f_{sp}
21	18.20	239.46	176607.9	0.9211
22	19.80	255.16	191045.1	0.9966
23	10.50	163.93	107129.2	0.5577
24	6.54	125.08	71397.3	0.3708
25	19.54	252.61	188699.0	0.9844
26	18.42	241.62	178593.0	0.9315
27	21.53	272.13	206655.2	1.0783
28	22.54	282.04	215768.7	1.1259
29	15.32	211.21	150621.1	0.7852
30	19.64	253.59	189601.4	0.9891
31	7.82	137.63	82947.0	0.4312
32	14.37	201.89	142049.0	0.7403
33	15.26	210.62	150079.7	0.7823
34	18.54	242.80	179675.8	0.9372
35	19.58	253.00	189060.0	0.9862
36	4.38	103.89	51907.1	0.2688
37	21.25	269.38	204128.7	1.0651
38	11.83	176.97	119130.1	0.6205

Table 7

Flexural strength of the samples 1-20 American bond wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
1	5.80	221.41	34233.4	0.16868
2	5.12	214.74	31910.0	0.15676
3	7.95	242.50	41579.5	0.20636
4	9.64	259.08	47353.9	0.23599
5	6.50	228.28	36625.2	0.18095
6	11.45	276.84	53538.3	0.26771
7	13.82	300.09	61636.1	0.30926
8	5.53	218.76	33310.9	0.16394
9	8.64	249.27	43937.1	0.21846
10	14.23	304.11	63037.0	0.31644
11	12.45	286.65	56955.1	0.28524
12	7.98	242.80	41682.0	0.20689
13	6.30	226.32	35941.8	0.17744
14	7.56	238.68	40247.0	0.19953
15	12.60	288.12	57467.6	0.28787
16	12.43	286.45	56886.8	0.28489
17	11.98	282.04	55349.2	0.277
18	14.25	304.31	63105.3	0.31679
19	13.54	297.34	60679.4	0.30435
20	7.65	239.56	40554.5	0.2011

Table 8

Flexural strength of the samples 21-38 American bond wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
21	7.42	237.30	39768.6	0.19707
22	8.54	248.29	43595.4	0.2167
23	9.42	256.92	46602.2	0.23213
24	6.42	227.49	36351.8	0.17954
25	10.54	267.91	50429.0	0.25176
26	10.26	265.16	49472.3	0.24685
27	11.98	282.04	55349.2	0.277
28	12.38	285.96	56715.9	0.28401
29	9.45	257.22	46704.7	0.23266
30	9.21	254.86	45884.7	0.22845
31	7.82	241.23	41135.3	0.20408
32	8.52	248.09	43527.1	0.21635
33	10.20	264.58	49267.3	0.2458
34	6.30	226.32	35941.8	0.17744
35	3.45	198.36	26203.9	0.12748
36	9.87	261.34	48139.8	0.24002
37	15.80	319.51	68401.4	0.34396
38	16.80	329.32	71818.2	0.36149

Table 9

Flexural strength of the samples 1-22 using Indian balanced bond wrench

S No	m2	Fsp	Msp	f_{sp}
1	3.30	104.18	25529.7	0.1292
2	13.12	200.52	89668.8	0.4632
3	11.22	181.88	77259.0	0.3986
4	8.90	159.12	62106.0	0.3197
5	12.54	194.83	85880.6	0.4435
6	19.53	263.40	131535.6	0.6812
7	14.82	217.19	100772.3	0.5210
8	17.60	244.47	118929.8	0.6156
9	15.82	227.00	107303.8	0.5551
10	15.30	221.90	103907.4	0.5374
11	6.30	133.61	45124.2	0.2313
12	8.20	152.25	57534.0	0.2959
13	11.10	180.70	76475.2	0.3945
14	9.60	165.99	66678.0	0.3435
15	5.10	121.84	37286.4	0.1904
16	4.30	113.99	32061.2	0.1632
17	8.20	152.25	57534.0	0.2959
18	5.50	125.76	39899.0	0.2041
19	14.30	212.09	97376.0	0.5034
20	15.20	220.92	103254.3	0.5340
21	16.30	231.71	110438.9	0.5714
22	18.20	250.35	122848.7	0.6360

Table 10

Flexural strength of the samples 23-44 using Indian balanced bond wrench

S No	m2	Fsp	Msp	
23	19.42	262.32	130817.1	0.6775
24	20.40	271.93	137217.9	0.7108
25	29.20	358.26	194694.9	1.0101
26	18.24	250.74	123110.0	0.6374
27	12.28	192.28	84182.4	0.4347
28	8.12	151.47	57011.4	0.2932
29	9.30	163.04	64718.6	0.3333
30	28.30	349.43	188816.6	0.9795
31	29.10	357.28	194041.8	1.0067
32	30.50	371.01	203185.8	1.0543
33	32.50	390.63	216248.8	1.1224
34	18.30	251.33	123501.8	0.6394
35	13.50	204.24	92150.8	0.4761
36	17.20	240.54	116317.2	0.6020
37	19.62	264.28	132123.4	0.6843
38	19.12	259.38	128857.7	0.6673
39	19.65	264.58	132319.3	0.6853
40	6.80	138.52	48389.9	0.2483
41	23.54	302.74	157726.8	0.8176
42	21.82	285.86	146492.6	0.7591
43	22.20	289.59	148974.6	0.7720
44	20.69	274.78	139112.1	0.7207

Table 11

Flexural strength of the samples 1-22 using Indian unbalanced bond wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
1	9.50	149.70	67057.9	0.3464
2	7.65	131.55	55205.1	0.2847
3	8.10	135.97	58088.2	0.2997
4	14.30	196.79	97810.9	0.5065
5	12.30	177.17	84997.2	0.4398
6	15.20	205.62	103577.1	0.5365
7	11.35	167.85	78910.6	0.4081
8	12.50	179.13	86278.5	0.4465
9	14.32	196.98	97939.1	0.5072
10	15.20	205.62	103577.1	0.5365
11	11.30	167.36	78590.3	0.4065
12	9.70	151.66	68339.3	0.3531
13	9.50	149.70	67057.9	0.3464
14	8.90	143.81	63213.7	0.3264
15	8.64	141.26	61548.0	0.3177
16	15.90	212.48	108062.0	0.5599
17	13.56	189.53	93069.8	0.4818
18	12.98	183.84	89353.8	0.4625
19	26.80	319.41	177897.0	0.9234
20	8.12	136.16	58216.4	0.3004

Table 12

Flexural strength of the samples 21-40 using Indian unbalanced bond wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
21	6.35	118.80	46876.2	0.2414
22	12.28	176.97	84869.0	0.4391
23	18.24	235.44	123054.1	0.6379
24	18.63	239.27	125552.8	0.6509
25	14.87	202.38	101462.9	0.5255
26	19.35	246.33	130165.7	0.6749
27	39.80	446.94	261186.5	1.3570
28	31.56	366.11	208393.8	1.0822
29	33.50	385.14	220823.2	1.1469
30	37.24	421.83	244784.9	1.2716
31	29.54	346.29	195451.9	1.0148
32	35.86	408.29	235943.4	1.2256
33	38.24	431.64	251191.8	1.3050
34	36.52	414.77	240172.0	1.2476
35	34.81	397.99	229216.2	1.1906
36	44.00	488.15	288095.5	1.4971
37	41.28	461.46	270668.7	1.4064
38	44.00	488.15	288095.5	1.4971
39	48.40	531.31	316285.8	1.6438
40	43.90	487.16	287454.8	1.4937

Table 13

Flexural strength of the samples 41-49 using Indian unbalanced bond wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
41	43.20	480.30	282970.0	1.4704
42	41.29	461.56	270732.8	1.4067
43	41.82	466.76	274128.4	1.4244
44	39.80	446.94	261186.5	1.3570
45	38.35	432.72	251896.6	1.3086
46	32.17	372.09	212302.0	1.1025
47	23.44	286.45	156369.9	0.8114
48	25.64	308.03	170465.0	0.8847
49	29.31	344.04	193978.3	1.0071

A Student t Test analysis has been carried out between Australian -American, Australian-Unbalanced wrench, Australian-Balanced wrench, American-Unbalanced, American-Balanced and Unbalanced-Balanced wrenches to calculate the means, variance and t-stat to allow a comparison of sets of results. Table 14 shows the method for interpreting Student's t Test carried out on two samples.

Table 14

Interpretation of student T-test

If	Then
Test statistic > critical value (i.e. $t > t_{crit}$)	Reject the null hypothesis
test statistic < critical value (i.e. $t < t_{crit}$)	Accept the null hypothesis
p value < α	Reject the null hypothesis
p value > α	Accept the null hypothesis

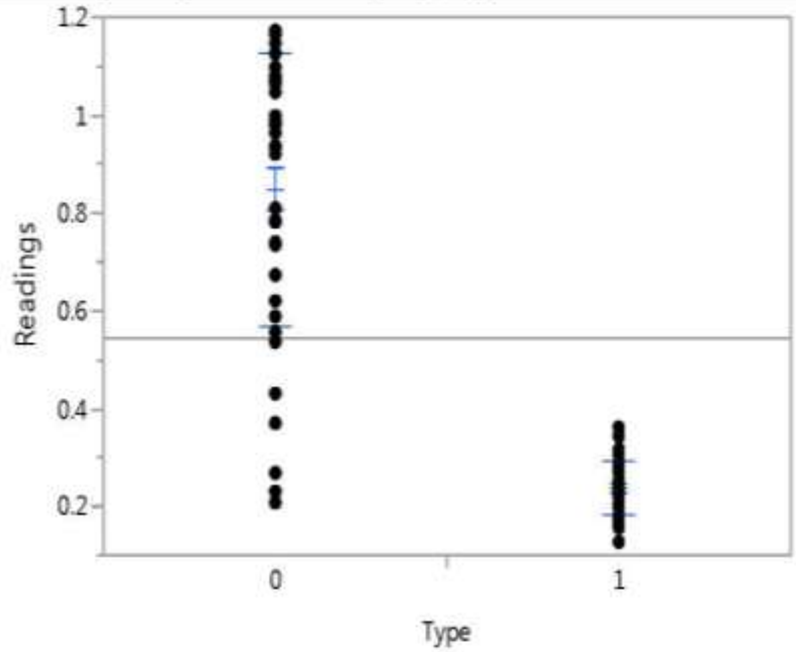
The null hypothesis is that there exists no bias between the flexural strength values from the four wrenches. The present test is a two sided test, and hence two tail values were used for the analysis.

If the (t statistic < t critical) and (p value > α) in all the t Test comparisons between the sample sets, we can accept the null hypothesis that the means are the same.

Figure 33 to Figure 38 show the results of the statistical analysis comparison.

Sheet1 - Fit Y by X of Readings by Type

Oneway Analysis of Readings By Type



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	38	0.849108	0.279509	0.04534	0.75724	0.94098
1	38	0.237591	0.055462	0.00900	0.21936	0.25582

t Test

1-0

Assuming unequal variances

Difference	-0.61152	t Ratio	-13.2287
Std Err Dif	0.04623	DF	39.90912
Upper CL Dif	-0.51808	Prob > |t|	<.0001*
Lower CL Dif	-0.70495	Prob > t	1.0000
Confidence	0.95	Prob < t	<.0001*

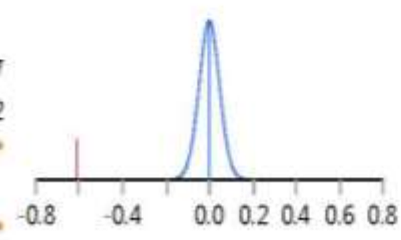
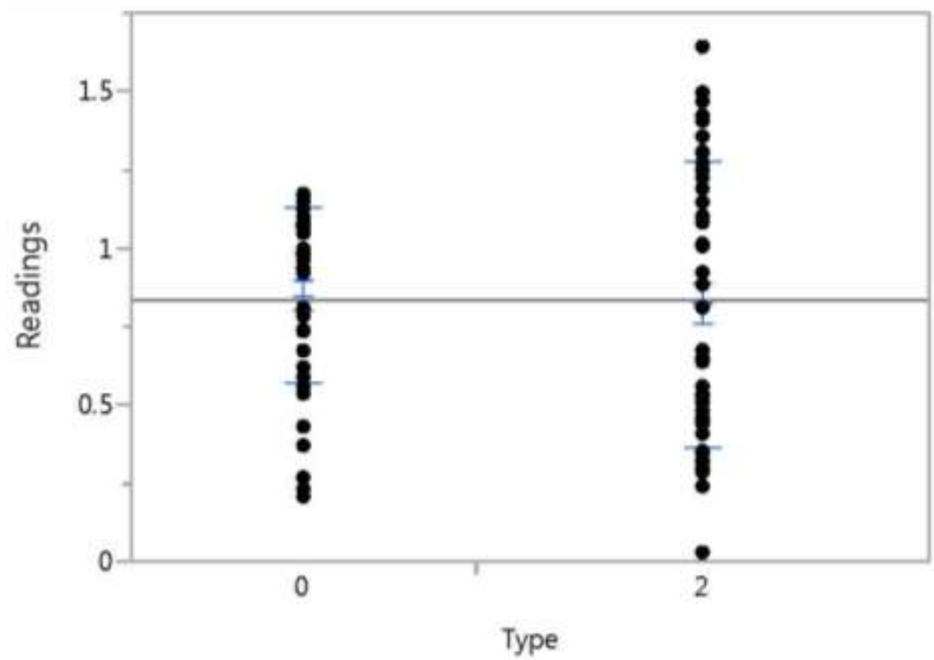


Figure 33: Australian- American bond wrench comparison

Sheet1 - Fit Y by X of Readings by Type

Oneway Analysis of Readings By Type



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	38	0.849108	0.279509	0.04534	0.75724	0.94098
2	50	0.822838	0.455424	0.06441	0.69341	0.95227

t Test

2-0

Assuming unequal variances

Difference	-0.02627	t Ratio	-0.33351
Std Err Dif	0.07877	DF	82.70315
Upper CL Dif	0.13040	Prob > |t|	0.7396
Lower CL Dif	-0.18294	Prob > t	0.6302
Confidence	0.95	Prob < t	0.3698

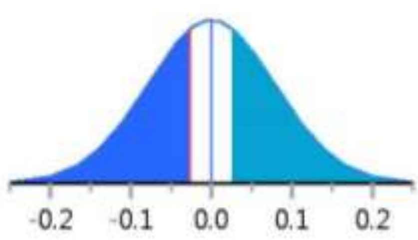
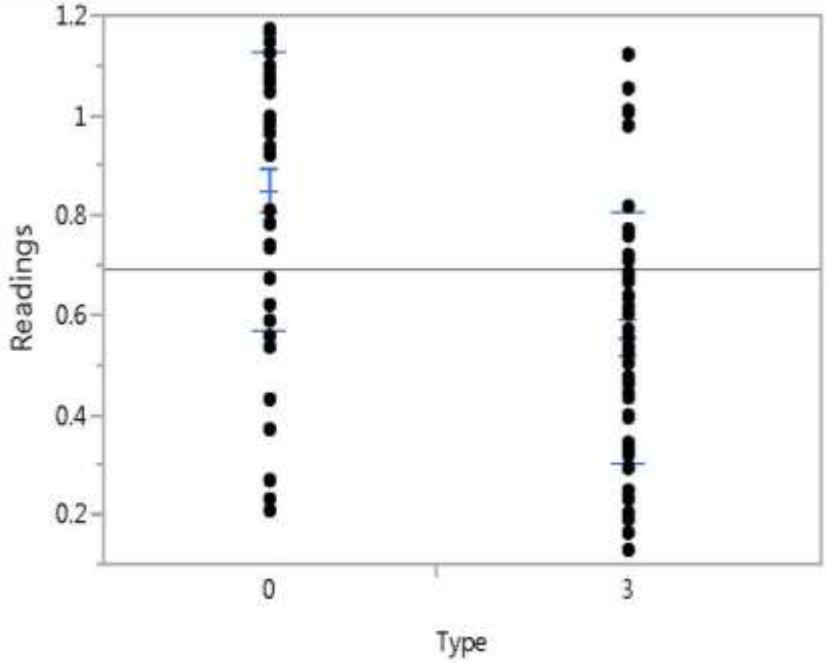


Figure 34: Australian- Indian unbalanced wrench comparison

Sheet1 - Fit Y by X of Readings by Type

Oneway Analysis of Readings By Type



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	38	0.849108	0.279509	0.04534	0.75724	0.94098
3	44	0.553638	0.251232	0.03787	0.47726	0.63002

t Test

3-0

Assuming unequal variances

Difference	-0.29547	t Ratio	-5.0012
Std Err Dif	0.05908	DF	75.16032
Upper CL Dif	-0.17778	Prob > |t|	<.0001*
Lower CL Dif	-0.41316	Prob > t	1.0000
Confidence	0.95	Prob < t	<.0001*

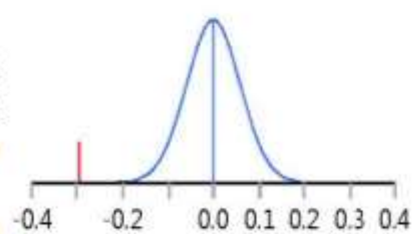
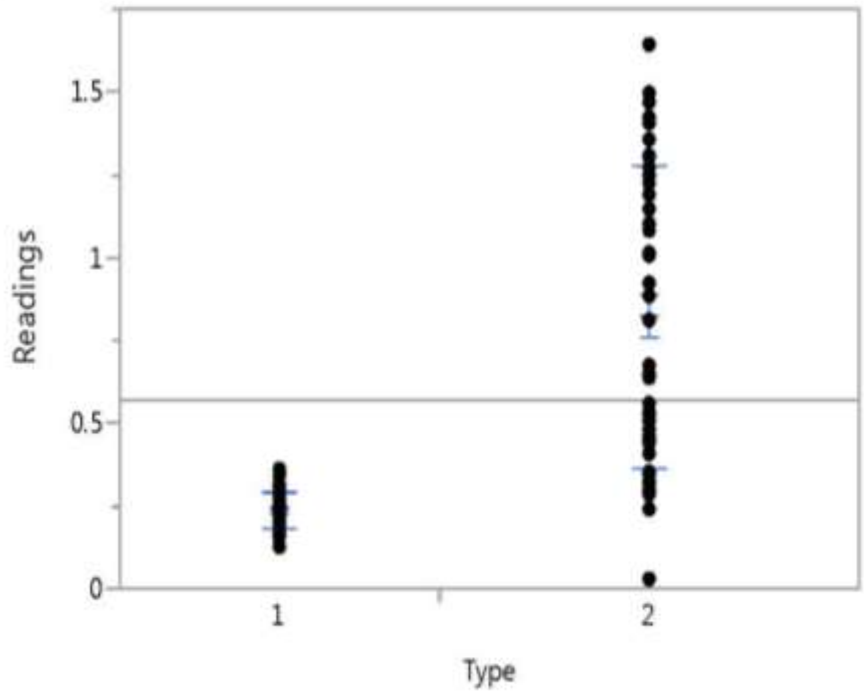


Figure 35: Australian- Indian balanced wrench comparison

Sheet1 - Fit Y by X of Readings by Type

Oneway Analysis of Readings By Type



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
1	38	0.237591	0.055462	0.00900	0.21936	0.25582
2	50	0.822838	0.455424	0.06441	0.69341	0.95227

t Test

2-1

Assuming unequal variances

Difference	0.585247	t Ratio	8.999368
Std Err Dif	0.065032	DF	50.90537
Upper CL Dif	0.715810	Prob > |t|	<.0001*
Lower CL Dif	0.454684	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

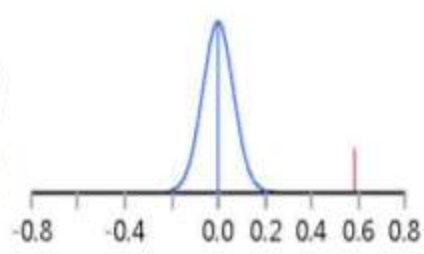
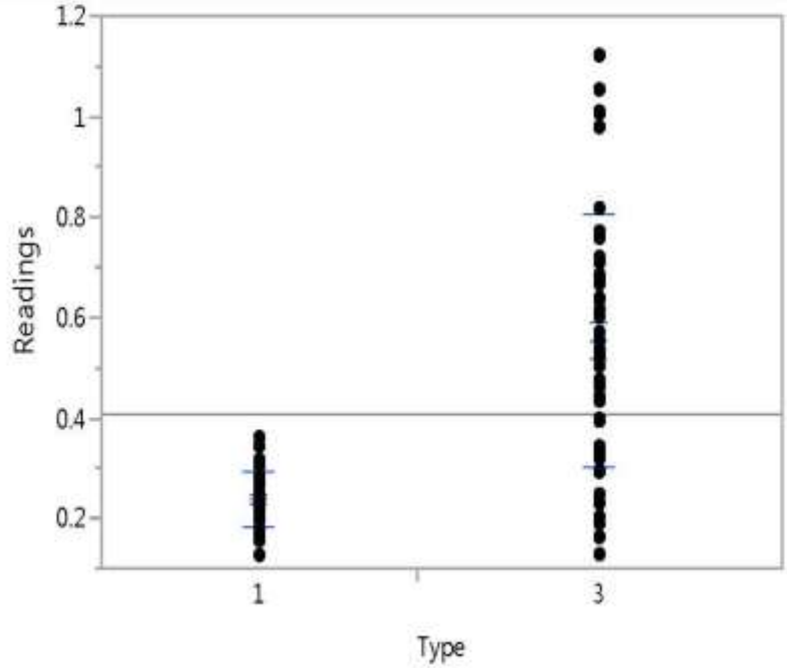


Figure 36: American- Indian unbalanced wrench comparison

Sheet1 - Fit Y by X of Readings by Type

Oneway Analysis of Readings By Type



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
1	38	0.237591	0.055462	0.00900	0.21936	0.25582
3	44	0.553638	0.251232	0.03787	0.47726	0.63002

t Test

3-1

Assuming unequal variances

Difference	0.316046	t Ratio	8.118597
Std Err Dif	0.038929	DF	47.81298
Upper CL Dif	0.394325	Prob > |t|	<.0001*
Lower CL Dif	0.237767	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

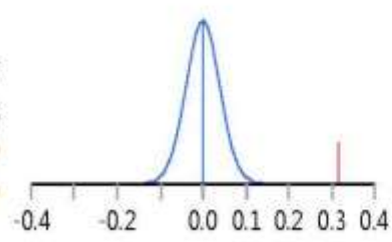
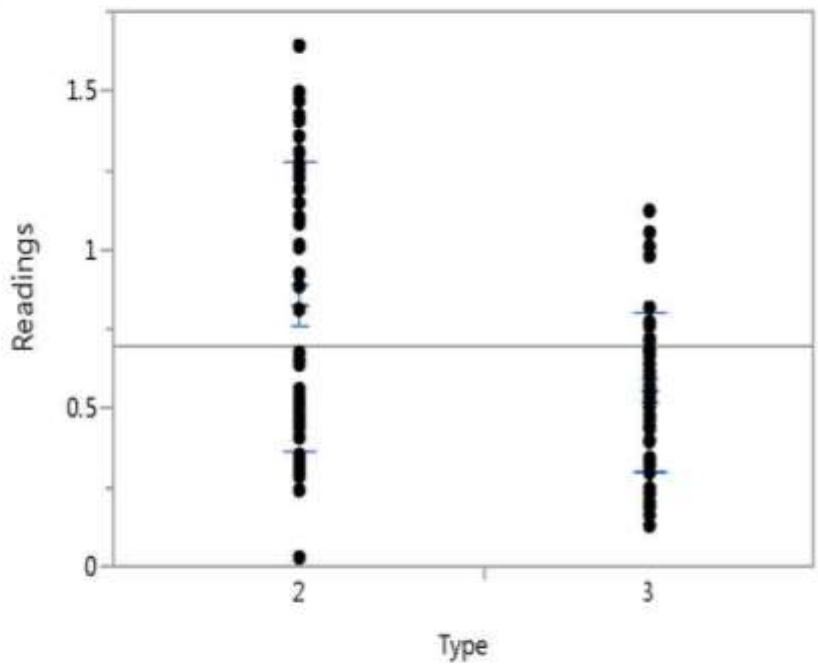


Figure 37: American- Indian balanced wrench comparison

Sheet1 - Fit Y by X of Readings by Type

Oneway Analysis of Readings By Type



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
2	50	0.822838	0.455424	0.06441	0.69341	0.95227
3	44	0.553638	0.251232	0.03787	0.47726	0.63002

t Test

3-2

Assuming unequal variances

Difference	-0.26920	t Ratio	-3.60291
Std Err Dif	0.07472	DF	78.10551
Upper CL Dif	-0.12045	Prob > |t|	0.0006*
Lower CL Dif	-0.41795	Prob > t	0.9997
Confidence	0.95	Prob < t	0.0003*

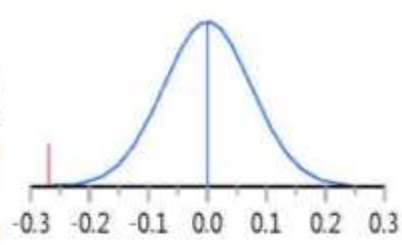


Figure 38: Indian unbalanced-Indian balanced wrench comparison

Summary of results

- From the above t test analysis
  - The mean of the values of the Australian bond wrench is 0.849 MPa
  - The mean of the values of the American bond wrench is 0.237MPa
  - The mean of the values of the Indian unbalanced wrench is 0.822MPa
  - The mean of the values of the Indian balanced wrench is 0.553MPa
- From the above six t test analysis, it can be found that the mean values of the Australian, Balanced and Unbalanced wrench are found to be similar.
- The scatter of the plots of Australian, Indian balanced and unbalanced wrench appears to be more spread in contrast with the American Wrench.
- The tests conducted with American wrench has shown that the mean (0.237 MPa) is drastically lower than the Australian (0.849 MPa), India balanced (0.553 MPa) and the unbalanced (0.822 MPa) wrenches. This can be attributed to the short moment arm and the bulkiness of the American wrench. Previous results from Chaudhari (2010) has also proved that there exists no bias in the values from the balanced and the unbalanced wrenches. McHargue (2013) had mentioned in his research that the values from Australian wrench were more sensitive to load than the American wrench.
- The above six t test analysis conforms to the previous studies and it can be noted that no bias existed between the values from Australian, Indian balanced and unbalanced wrenches, whereas the American wrench forecasted values which did not align with the other three wrenches used.

CHAPTER V

CONCLUSIONS

Bond strength is one of the most important factors that affect the performance of a joint under various loading conditions. The flexural bond strength of a joint can be measured using a bond wrench. The first of the bond wrenches was developed in 1980s in an Australian laboratory. In the past few years a variety of bond wrenches with different designs have been manufactured.

Four bond wrenches, termed the Australian, American, Indian balanced and unbalanced have been developed at TAMU. Two graduate students developed the Indian unbalanced and balanced bond wrench. An Australian bond wrench was manufactured in 2011 and subsequently in 2012 an ASTM C 1072 Bond Wrench was developed. The Australian and the American wrenches are unbalanced imparting a torque to the prism upon placement. Among the Indian wrenches, one wrench is balanced and the other is unbalanced. The Indian balanced and the unbalanced wrenches vary only with respect to the upper clamping buckets.

A number of studies have been conducted before at TAMU to study the bias between the different wrenches for the mean flexural strength obtained using a set of masonry prisms. Previous researchers have found out that no unacceptable bias existed in the flexural strength values forecasted using the Indian balanced and unbalanced wrench. The results have also shown that there exists a bias between American Bond Wrench and Australian Bond wrenches. The Australian ones showed significantly higher than the American bond wrenches for similar types of samples. Hence it was suggested that the tests be carried out by replacing the cement with Portland cement.

This experimental research uses Portland cement and aims to make a comparison of bond strength values forecasted by the Australian, American, Balanced and Unbalanced Indian wrenches and check the bias among them.

For the experimental purposes, a total of 50 prisms were built. Each prism comprised of 6 bricks with 5 joints, and all the bricks used were Texan bricks. The mortar used here was 1:1:6, and Portland cement was used. The samples were cured for a period of 28 days before the experiment was carried out. All the experiments were carried out under the same weather conditions. The first set of 25 prisms was tested using Australian and the American bond wrench. The second set of 25 prims was tested using the Indian balanced and Indian unbalanced wrenches.

A Student's t Test analysis was run between the flexural strength values of the four wrenches. From the plots, it can be inferred that the mean value of the American wrench was low when compared with the mean values of the other three wrenches. The plots of Australian bond wrench and Indian unbalanced were quite similar.

It can be concluded that the values forecasted using American bond wrench were statistically different from the other three wrenches, and the reason can be noted as the difficulty in using the American bond wrench.

Further research is recommended using the Texas red brick.

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